

Characterization of two-layer diffuse media by reflection of gigahertz photon density waves

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Diffuse reflected light is used to characterize optical properties of two-layer turbid media. The source is modulated in gigahertz frequencies. The phase and amplitude of analytical reflectance is fitted to the data generated by adding 2.5% noise in amplitude and 1° noise in phase to the solution of diffusion approximation in gigahertz frequency regime. The extracted optical properties are in good agreement with the real values.

Keywords: two-layer, diffusion theory, photon migration, gigahertz modulation frequency.

I. INTRODUCTION

There are many techniques to image living tissues non-invasively such as anatomical (MRI, X-ray...) and biochemical (PET, fMRI, optical methods). Both imaging modalities are used in a complimentary way to distinguish an abnormal tissue from the rest of the healthy tissues. While, x-ray imaging employs ionizing radiation, MRI is very expensive and not portable. PET requires the injection of a radioactive substance into the blood stream and emission is mapped; hence it is invasive and expensive system as well. Therefore, an inexpensive, portable apparatus, which can provide both structural and dynamical changes, is a very attractive feature. Near-infrared (NIR) light techniques fulfill these requirements.

In NIR region, tissue optical properties (absorption and scattering) are being mapped. Light absorbing and scattering structures carry information about tissue function and structure. Therefore, quantification of optical property changes gives information about disease-related functional and structural changes.

The probing depth in the tissue depends on the modulation frequency of the source. Because of the attenuation, at higher modulation frequencies, the penetration will be at the surface, or skin layers. It is reported that for modulation frequencies between several hundred megahertz and a few gigahertz, the properties of muscle tissue of up to 4-8 mm deep can be analyzed [1]. It is suggested that the technique might be of use for evaluating the depth of necrosis and blood volume fraction in deep burns. The non-invasive determination of the depth of severe burns has been used for clinical applications.

Tromberg et al. used an apparatus which goes up to 1.5

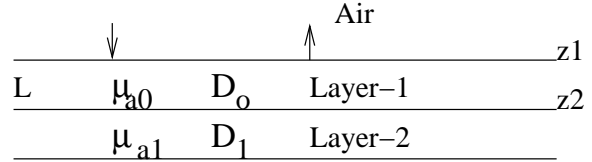


Fig. 1. Geometry of two-layer model

GHz modulation frequencies to determine optical properties of two-layer problem and they suggest that going even higher than 2 GHz may improve the accuracy of extracting all five free parameters in a two-layer system (absorption and scattering coefficients for each layer + thickness of the layer) [2]. This is due to the increased scattering sensitivity and better spatial localization of high-frequency diffuse photon density waves (DPDW's). The advantages of gigahertz DPDW's are that they are more sensitive to boundaries, and therefore in reconstruction, the artifacts coming from the mismatch at the boundaries will be eliminated [3].

In section II we show the analytical expression for two-layer reflectance. In section III we obtain the optical parameters by fitting the reflectance of theory to the experiment.

II. THEORY OF TWO-LAYER REFLECTANCE

The investigated turbid medium is shown in Fig-1.

The thickness of the first layer is L , and optical parameters are (μ_{a0}, μ'_{s0}) , for absorption and scattering coefficients, respectively. Second layer is semi-infinite with optical parameters (μ_{a1}, μ'_{s1}) . It is assumed that the two layers have the same refractive index $n = 1.33$. The diffusion equation in the gigahertz regime is [4]:

$$D\nabla^2 U(r, t) - \mu_a U(r, t) = (1 + 3D\mu_a) \frac{1}{c} \frac{\partial}{\partial t} U(r, t) - q + \frac{3D}{c^2} \frac{\partial^2 U(r, t)}{\partial t^2} \quad (1)$$

where $U(r, t) = U(r) \exp(i\omega t)$ is the average intensity and q is the source term, c is the speed of light and D is the diffusion coefficient. When a point light source is modulated with a frequency ω , $U(r, t)$ represents gigahertz DPDW's with a wave vector, $k_o = (-\mu_a/D + i\frac{\omega n}{cD}(1 + 3\mu_a D) + 3\frac{\omega^2}{c^2}n^2)^{1/2}$.

At any constant z -plane, $U(r)$ can be expressed in angular spectrum representation as a superposition of

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plane waves with amplitude $\vec{A}(\vec{K})$ and wave vector $\vec{k} = (\vec{K}, q)$, $|\vec{k}| = k_o$ [5]:

$$U(\vec{R}, z) = \int \vec{A}(\vec{K}) \exp(i\vec{K} \cdot \vec{R} + iq|z|) d\vec{K} \quad (2)$$

where $\vec{R} = (x, y)$, $\vec{K} = (K_x, K_y)$, and $K^2 + q^2 = k_o^2$.

Because it is simple and physically illustrative, we solve the two-layer problem by successively adding multiple reflections and transmissions at the interfaces [5,6]. Considering all multiple reflections from the interfaces, the total reflection coefficient at $z = 0$ is :

$$U_R = U_{z1}^{inc} T_{10} + U_{z1}^{inc} \frac{R_{10} \exp(2iq_1 L) R_{12} T_{10}}{1 - R_{10} \exp(2iq_1 L) R_{12}} + U_{z2}^{inc} \frac{R_{12} \exp(2iq_1 L) T_{10}}{1 - R_{10} \exp(2iq_1 L) R_{12}} \quad (3)$$

where $U_{z1,z2}^{inc}$ are the incident fields at $z1$ and $z2$ respectively, R_{ij} and T_{ij} are the reflection and transmission coefficients on going from medium i onto medium j and q is as before:

$$q(\vec{K}) = \sqrt{k_o^2 - |\vec{K}|^2} \quad (4)$$

III. FITTING RESULTS AND CONCLUSION

Experimental data is obtained by simulating the forward solution of diffusion equation with an addition of amplitude noise of 2.5% and phase noise of 1° , because instrumental noises are in this range [2]. The optical parameters are taken as the same as Tromberg et al. for comparison reasons [2]. The simulated data are fitted to the analytical result for reflection coefficient, Eq-4. To perform fitting, Levenberg-Macquart Matlab fitting algorithm is used to extract the optical parameters of second layer, because in most experimental setups first-layer properties are already known. Table-1,2 shows the fitting results for modulation frequencies of $\omega = 1, 2GHz$. The thickness of the top layer is taken as $L = 5mm$. As seen from the table that the fitted values are in good agreement with the real values.

TABLE I
 $\omega = 1GHz$

Coefficients	Med-1	Med-2	Fitted Med-2
μ_a	0.05	0.056	0.0515
μ'_s	3.1	6.2	6.226

TABLE II
 $\omega = 2GHz$

Coefficients	Med-1	Med-2	Fitted Med-2
μ_a	0.05	0.056	0.0637
μ'_s	3.1	6.2	6.149

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